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(54) Casting thixotropic metals

(57) Molten metal in a mold (11) is cooled under controlled conditions while it is mixed under the influence of a moving non-zero magnetic field. The magnetic field is provided across the full cross section of the mold and over the entire solidification zone resulting in a magnetomotive stirring force of sufficient magnitude to provide mixing of the molten metal to form the thixotropic slurry. Preferably, a two pole induction motor stator (27) is used to generate the magnetic field.

Fig.1.

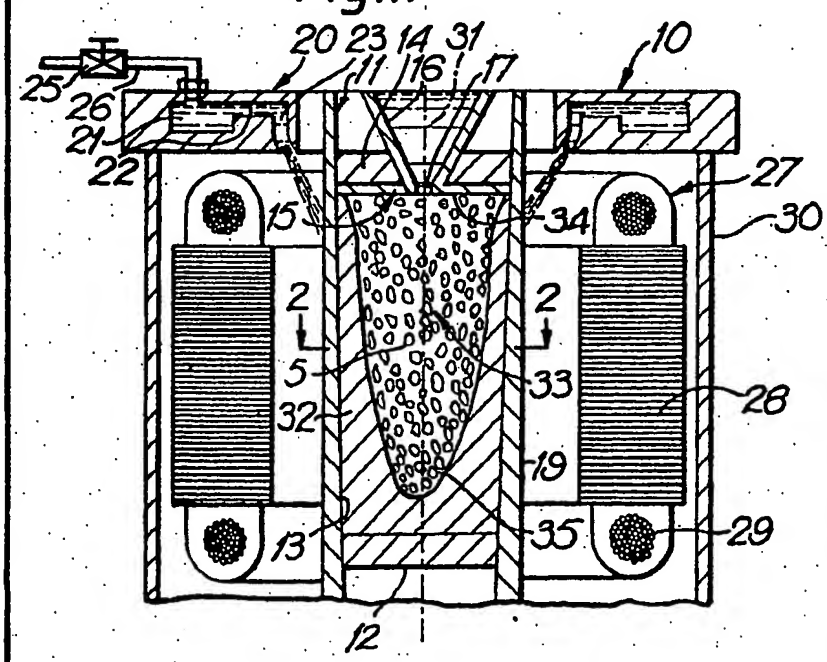

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Fig.1.

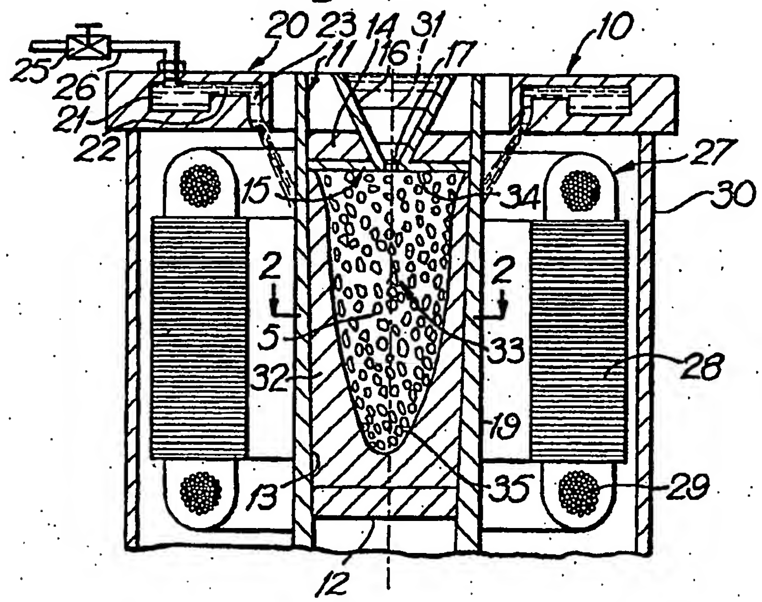

Fig.2.

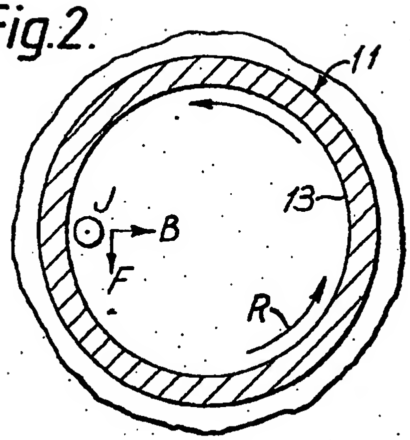

Fig.3.

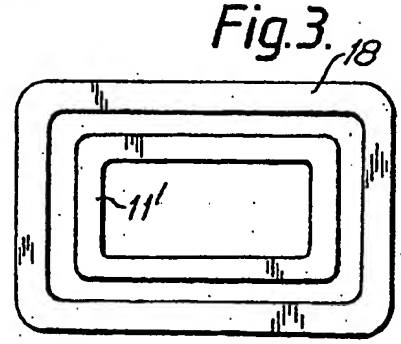

Fig.4.

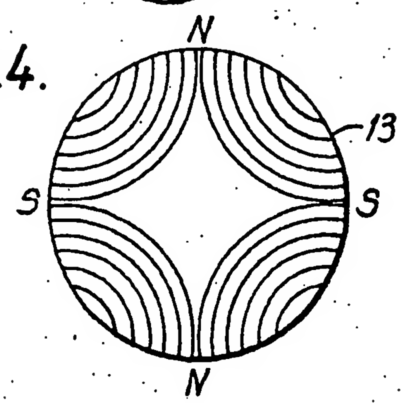

Fig.5

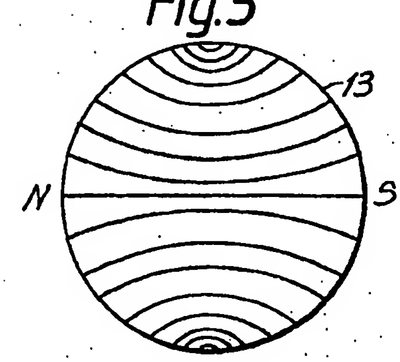

Fig.6.

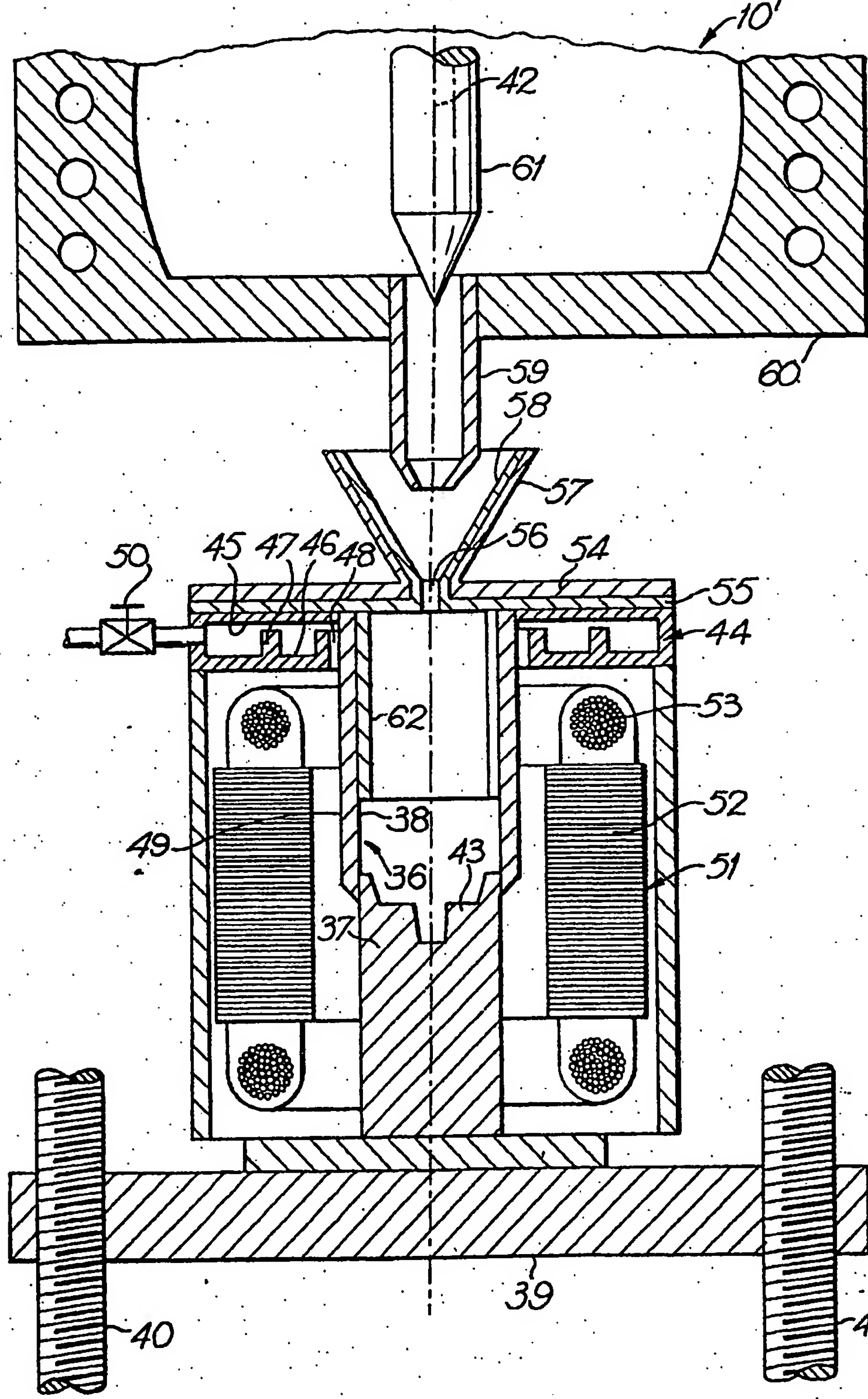
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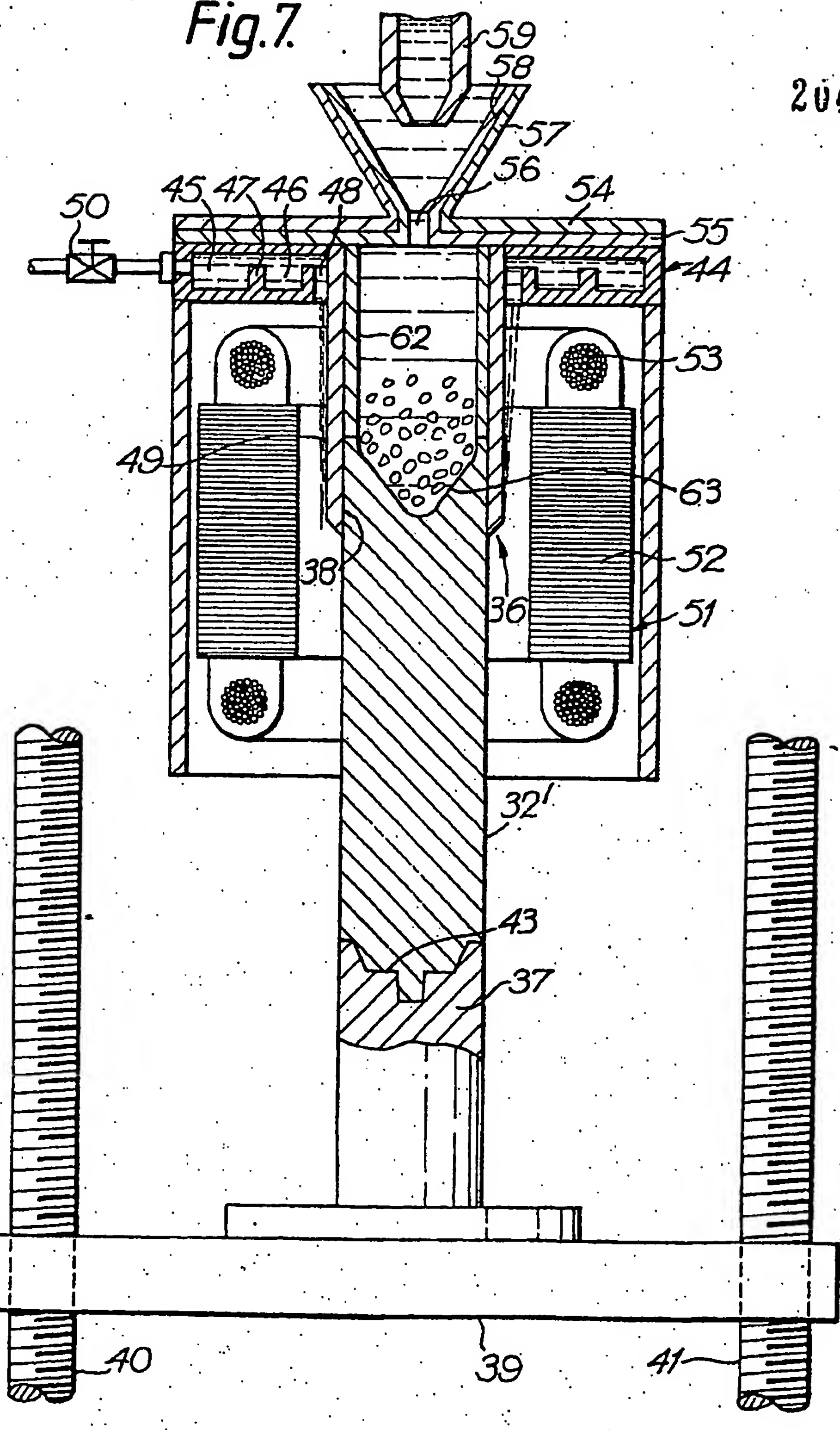
Fig.7.



SPECIFICATION

Process and apparatus for casting metals and alloys

This invention relates to a process and apparatus for forming semi-solid thixotropic alloy slurries for use in applications such as rheocasting, thixocasting, or thixoforging.

The known methods for producing semi-solid thixotropic alloy slurries include mechanical stirring and inductive electromagnetic stirring. The processes for producing such slurries with a structure suitable for casing require a balance between the shear rate imposed by the stirring and the solidification rate of the material being cast.

In the mechanical stirring process, the molten metal flows downwardly into an annular space in a cooling and mixing chamber. Here the metal is partially solidified while it is agitated by the rotation of a central mixing rotor to form the desired thixotropic metal slurry for rheocasting. The mechanical stirring approaches suffer from several inherent problems. The annulus formed between the rotor and the mixing chamber walls provides a low volumetric flow rate of thixotropic slurry. There are material problems due to the erosion of the rotor, and it is difficult to couple mechanical agitation to a continuous casting system.

In the continuous rheocasting processes described in the art the mixing chamber is arranged above a direct chill casting mold. The transfer of the metal from the mixing chamber to the mold can result in oxide entrainment. This is a particularly acute problem when dealing with reactive alloys such as aluminum, which are susceptible to oxidation. The volumetric flow rates achievable by this approach are inadequate for commercial application.

The slurry is thixotropic, thus requiring high shear rates to effect flow into the continuous casting mold. Using the mechanical approach, one is likely to get flow lines due to interrupted flow and/or discontinuous solidification. The mechanical approach is also limited to producing semi-solid slurries, containing from about 30 to 60% solids. Lower fractions of solids improve fluidity but enhance undesired coarsening and dendritic growth during completion of solidification. It is not possible to get significantly higher fractions of solids because the agitator is immersed in the slurry.

In order to overcome the aforenoted problems inductive electromagnetic stirring has been proposed. While the indirect nature of this electromagnetic stirring is an improvement over the mechanical process, there are still limitations imposed by the nature of the stirring technique.

With AC inductive stirring, the maximum electromagnetic forces and associated shear are limited to the penetration depth of the induced currents. Accordingly, the section size that can be effectively stirred is limited due to the decay of the induced forces from the periphery to the interior of the melt. This is particularly aggravated when a solidifying shell is present. The inductive electromagnetic stirring process also requires high power consumption and the resistance heating of the stirred metal is significant. The resistance heating in turn increases the required amount of heat extraction of solidification.

The pulsed DC magnetic field technique is also effective, however, it is not as effective as desired because the force field rapidly diverges as the distance from the DC electrode increases. Accordingly, a complex geometry is required to produce the required high shear rates and fluid flow patterns to insure production of slurry with a proper structure. Large magnetic fields are required for this process and, therefore, the equipment is costly and very bulky.

According to one aspect of the invention there is provided an apparatus for forming a semi-solid thixotropic alloy slurry, consisting of degenerate dendrite primary solid particles in a surrounding matrix of molten metal, said apparatus comprising:

means for containing molten metal,

means for controllably cooling said molten metal in said containing means, and

means for mixing said molten metal for shearing dendrites formed in a solidification zone as said molten metal is cooled for forming said slurry;

wherein said mixing means comprises means for generating a moving, non-zero magnetic field across said cross section of said containing means and over said entire solidification zone, said moving magnetic field providing a magnetomotive stirring force of sufficient magnitude to provide said mixing of said molten metal.

According to another aspect of the invention there is provided a process for forming a semi-solid thixotropic alloy slurry, said slurry comprising degenerate dendrite primary solid particles in a surrounding matrix of molten metal, said process comprising:

providing a means for containing molten metal having a desired cross section;

controllably cooling said molten metal in said containing means; and

generating a moving, non-zero magnetic field across said cross section of said containing means and over said entire solidification zone, said moving magnetic field providing a magnetomotive stirring force of sufficient magnitude to provide mixing of said molten metal.

Magnetohydromagnetic motion associated with a rotating magnetic field generated by a two pole multiphase motor stator is preferred to achieve the required high shear rates for

producing thixotropic semi-solid alloy slurries. Two pole induction motor stators are fabricated such that a magnetic field is always present between opposing poles of the motor. We have found that a two pole motor stator is required to provide proper stirring of a thixotropic metal slurry. A two pole motor stator provides a non-zero magnetic field across the full cross section of the melt that is to be stirred. The force field is also tangential to the mold wall which maximizes the effectiveness of the shearing off of dendrites as they grow and it is in a direction generally normal to the dendrite growth direction.

Using such a rotating magnetic field as the loss of magnetic field strength due to the presence of solidifying metal is small due to the low frequency that is used. The apparatus has a relatively low power consumption so that there is very little resistance heating of the melt being stirred.

In one embodiment, a static casing system is provided wherein a mold is arranged with a two pole polyphase induction motor stator about it. The motor stator is arranged circumferentially about the mold. To insure proper mixing of the slurry the stator length is preferably selected to provide a sufficient magnetic force field which extends over the full length of the solidification zone. To form the desired semi-solid slurry molten metal is poured into the mold and cooled under controlled conditions while the rotating electromagnetic field provided by the stator is present during the entire casting process. All dendrites which are formed at the mold surface or solidification front are readily sheared off due to the flow of the molten metal and slurry produced by the rotating magnetic field.

A partially enclosing cover means is preferably provided to prevent spillout of the slurry or molten metal as it is stirred.

In another embodiment the thixotropic slurry is cast in a continuous or semi-continuous manner. In this embodiment the molten metal is poured into a continuous casting mold which is surrounded by a two pole multiphase induction motor stator in the same manner as in the previous embodiment. The molten metal is poured into the top of the mold. It is stirred by the rotating electromagnetic field as it is cooled under controlled conditions to produce the desired thixotropic slurry. The solidifying slurry is then withdrawn from the bottom of the mold in a continuous or semi-continuous manner. Preferably, the continuous casting mold also includes a cover to prevent spillout of the molten metal and slurry as it is stirred. Further, it is preferred that the continuous casting mold include an upper portion or hot-top having a low rate of heat extraction wherein the molten metal is contained in a molten condition with little if any solidification occurring, followed by a second portion having a higher rate of heat extraction wherein solidification under the influence of the rotating magnetic field produces the desired semi-solid thixotropic slurry.

Embodiments of the invention will now be described with reference to the accompanying drawings, in which:–

Figure 1 is a schematic cross-sectional view of a static casting mold,

Figure 2 is a partial cross-sectional view along the line 2–2 in Fig. 1;

Figure 3 is a schematic bottom view of a non-circular mold and linear induction motor stator arrangement;

Figure 4 is a schematic representation of the lines of force at a given instant generated by a four pole induction motor stator;

Figure 5 is a schematic representation of the lines of force at a given instant generated by a two pole motor stator;

Figure 6 is a schematic representation in partial cross section of an apparatus for continuously or semi-continuously casting a thixotropic semi-solid metal slurry and,

Figure 7 is a schematic representation in partial cross section of the apparatus of Fig. 6 during a casting operation.

In the background of this application there have been described a number of techniques for forming semi-solid thixotropic metal slurries for use in rheocasting, thixocasting, thixoforging, etc. Rheocasting as the term is used herein refers to the formation of a semi-solid thixotropic metal slurry, directly into a desired structure, such as a billet for later processing, or a die casting formed from the slurry. Thixocasting or thixoforging respectively as the terms are used herein refer to processing which begins with a rheocast material which is then reheated for further processing such as die casting or forging.

The processes described herein are intended to provide rheocast material for immediate processing or for later use in various application of such material, such as thixocasting and thixoforging. The advantages of rheocasting include improved casting soundness as compared to conventional die casting. This results because the metal is partially solid as it enters the mold and, hence, less shrinkage porosity occurs. Machine component life is also improved due to reduced erosion of dies and molds and reduced thermal shock associated with rheocasting.

The metal composition of a thixotropic slurry comprises primary solid discrete particles and a surrounding matrix. The surrounding matrix is solid when the metal composition is fully solidified and is liquid when the metal composition is a partially solid and partially liquid slurry. The primary solid particles comprise degenerate dendrites or nodules which are generally spheroidal in shape. The primary solid particles are made up of a single phase or a plurality of phases having an average composition different from the aver-

age composition of the surrounding matrix in the fully solidified alloy. The matrix itself can comprise one or more phases upon further solidification.

Conventionally solidified alloys have branched dendrites which develop interconnected networks as the temperature is reduced and the weight fraction of solid increases. In contrast thixotropic metal slurries consist of discrete primary degenerate dendrite particles separated from each other by a liquid metal matrix, potentially even up to solid fractions of 80 weight percent. The primary solid particles are degenerate dendrites in that they are characterized by smoother surfaces and a less branched structure which approaches a spheroidal configuration. The surrounding solid matrix subsequent to the formation of the primary solids and contains one or more phases of the type which would be obtained during solidification of the liquid alloy in a more conventional process. The surrounding solid matrix comprises dendrites, single or multiphased compounds, solid solution, or mixtures of dendrites, and/or compounds and/or solid solutions.

Referring now to Fig. 1, the apparatus 10 shown comprises a cylindrical mold 11 for rheocasting a thixotropic metal slurry as described above in a static or non-continuous manner. The mold 11 is formed of any desired nonmagnetic material, such as copper, copper alloy, stainless steel or the like. The bottom 12 of the mold 11 comprises a plate sealingly secured e.g. by a tight mechanical fit to the tapered cylindrical wall 13. The top end of the mold 11 includes a partially enclosing cover plate 14 similarly secured to the mold wall 13. The cover plate 14 has a ceramic liner 15 internally of the mold 11 and a ceramic funnel 16 communicating with an opening 17 in the cover 14 through which molten metal is introduced into the mold 11. The purpose of the cover plate 14 and liner 15 is to prevent spillage of molten metal from the mold during the stirring operation. The funnel 16 serves to direct the molten metal into the mold 11.

Referring to Fig. 2 it can be seen that the mold wall 13 is cylindrical. The apparatus 10 is adapted for making cylindrical ingots utilizing a conventional two pole polyphase induction motor stator for stirring. However, the techniques described herein are not limited to the formation of a cylindrical ingot cross section since it is possible to achieve a transversely or circumferentially moving magnetic field with a non-cylindrical mold 11 as in Fig. 3. In the embodiment of Fig. 3 the mold 11 has a rectangular cross section surrounded by a polyphase rectangular induction motor stator 18. The magnetic field moves or rotates around the mold 11 in a direction normal to the longitudinal axis of the casting which is being made.

Referring again to Figs. 1 and 2, the molten metal which is poured into the mold 11 through the opening 17 is cooled within the mold 11 under controlled conditions by means of water sprayed upon the outer surface 19 of the mold 11 from an en-compassing manifold 20. By controlling the rate of water flow against the mold surface 19 the rate of heat extraction from the molten metal within the mold 11 can be controlled. The coolant application manifold 20 is of a conventional design comprising an inlet chamber 21 connected by a relatively narrow slot 22 to an output chamber 23 which discharges the water or other desired coolant through a discharge slot 24. The discharge slot 24 is angled to direct the water against the outer surface 19 of the mold 11. A valve 25 in the inlet connection 26 to the inlet chamber 21 of the manifold 20 is used to control the rate of water flow from the manifold 20 and thereby the rate of heat extraction. In the apparatus 10 a manually operated valve 25 is shown, however, if desired this could be an electrically operated valve.

In order to provide a means for stirring the molten metal within the mold 11 to form the desired thixotropic slurry a two pole multiphase induction motor stator 27 is arranged surrounding the mold 11. The stator 27 is comprised of iron laminations 28 about which the desired windings 29 are arranged in a conventional manner to provide a three-phase induction motor stator. The motor stator 27 is mounted within a motor housing 30. The manifold 20 and the motor stator 27 are arranged concentrically about the axis 31 of the mold 11 and casting 32 formed within it.

It is preferred to utilize a two pole three-phase induction motor stator 27. One feature of the two pole motor stator 27 is that there is a non-zero field across the entire cross section of the mold 11. It is, therefore, possible to solidify a casting having the desired rheocast structure over its full cross section.

Fig. 4 shows the instantaneous lines of force for a four pole induction motor stator at a given instant in time. It is apparent that the centre of the mold does not have a desired magnetic field associated with it. Therefore, the stirring action is concentrated near the wall 13 of the mold 11. In comparison thereto, a two pole induction motor stator as shown in Fig. 5 generates instantaneous lines of force at a given instant which provide a non-zero field across the entire cross section of the mold 11. The two pole induction motor stator 27 also provides a higher frequency of rotation or rate of stirring of the slurry S for a given current frequency than the four pole approach of Fig. 4.

Referring again to Fig. 2, a further feature of the rotary magnetic field stirring is illustrated. In accordance with Fleming's right-

hand rule for a given current J in a direction normal to the plane of the drawing the magnetic flux vector B extends radially inwardly of the mold 11 and the magnetic stirring force vector F extends generally tangentially of the mold wall 13. This sets up within the mold cavity a rotation of the molten metal in the direction of arrow R which generates the desired shear for producing the thixotropic slurry S. The force vector F is also tangential to the heat extraction direction and is normal to the direction of dendrite growth. This maximizes the shearing of the dendrites as they grow.

It is preferred that the stirring force field generated by the stator 27 extend over the full solidification zone 33 of molten metal and thixotropic metal slurry S. Otherwise the structure of the casting will comprise regions within the field of the stator 27 having a rheocast structure and regions outside the stator field tending to have a non-rheocast structure. In the embodiment of Fig. 1 the solidification zone 33 preferably comprises the sump of molten metal and slurry S within the mold 11 which extends from the top surface 34 to the solidification front 35 which divides the solidified casting 32 from the slurry S. The solidification zone 33 extends at least from the region of the initial onset of solidification and slurry formation in the sump to the solidification front 35.

To form a rheocasting 32 utilizing the apparatus 10 of Fig. 1 molten metal is poured into the mold cavity while the motor stator 27 is energized by a suitable three-phase AC current of a desired magnitude and frequency. After the molten metal is poured into the mold cavity it is stirred continuously by the rotating magnetic field produced by the motor stator 27. Solidification begins from the mold wall 13. The highest shear rates are generated at the stationary mold wall 13 or at the advancing solidification front 35. By properly controlling the rate of solidification by any desired means as are known in the prior art the desired thixotropic slurry S is formed.

The induction motor stator 27 which provides the stirring force needed to produce the degenerate dendrite rheocast structure can be readily placed either above or below the primary cooling manifold 20 as desired. Preferably, however, the induction motor stator 27 and mold 11 are located below the cooling manifold 20.

Referring to Figs. 6 and 7 an apparatus 10′ for continuously or semi-continuously rheocasting thixotropic metal slurries is shown. The mold 36 is adapted for continuous or semi-continuous rheocasting. The mold 36 may be formed of any desired nonmagnetic material such as stainless steel, copper, or copper alloy as in the previous embodiment. However the bottom block 37 of the mold 36 is arranged for movement away from the mold 36 as the casting forms a solidifying shell. The movable bottom block 37 comprises a standard direct chill casting type bottom block.

The bottom block 37 is formed of metal and is arranged for movement between the position shown in Fig. 6 wherein it sits up within the confines of the mold wall 38 and a position away from the mold 36 as shown in Fig. 7. This movement is achieved by supporting the bottom block 37 on a suitable carriage 39. Lead screws 40 and 41 or hydraulic means are used to raise and lower the bottom block 37 at a desired casting rate in accordance with conventional practice. The bottom block 37 is arranged to move axially along the mold axis 42. It includes a cavity 43 into which the molten metal is initially poured and which provides a stabilizing influence on the resulting casting as it is withdrawn from the mold 36.

A cooling manifold 44 is arranged circumferentially around the mold wall 38. The particular manifold shown includes a first input chamber 45, a second chamber 46 connected to the first input chamber by a narrow slot 47. A discharge slot 48 is defined by the gap between the manifold 44 and the mold 36. A uniform curtain of water is provided about the outer surface 49 of the mold 36. A suitable valving arrangement 50 is provided to control the flow rate of the water discharged in order to control the rate at which the slurry S solidifies.

As in the previous embodiment, a two pole three-phase inductor motor stator 51 is arranged concentrically about the mold 36 so that the magnetic forces generated by the stator act upon the slurry S over its complete zone of solidification. The stator comprises laminations 52 and three-phase windings 53.

A partially enclosing cover 54 is utilized to prevent spill out of the molten metal and slurry S due to the stirring action imparted by the magnetic field of the motor stator 51. The cover 54 comprises a metal plate arranged above the manifold 44 and separated therefrom by a suitable ceramic liner 55. The cover 54 includes an opening 56 through which the molten metal flows into the mold cavity. Communicating with the opening 56 in the cover 54 is a funnel 57 for directing the molten metal into the opening 56. A ceramic liner 58 is used to protect the metal funnel 57 and the opening 56. As the thixotropic metal slurry S rotates within the mold 36, cavity centrifugal forces cause the metal to try to advance up the mold wall 38. The cover 54 with its ceramic lining 55 prevents the metal slurry from advancing or spilling out of the mold 36 cavity and causing damage to the apparatus 10′.

Situated directly above the funnel 57 is a downspout 59 through which the molten metal flows from a suitable furnace 60. A

valve member 61 associated in a coaxial arrangement with the downspout 59 is used in accordance with conventional practice to regulate the flow of molten metal into the mold 36.

The furnace 60 may be of any conventional design, it is not essential that the furnace be located directly above the mold 36. In accordance with conventional direct chill casting processing the furnace may be located laterally displaced therefrom and be connected to the mold 36 by a series of troughs or launders.

Under normal solidification conditions, the periphery of the ingot 32′ will exhibit a columnar dendritic grain structure. Such a structure is undesirable and detracts from the overall advantages of the rheocast structure which occupies most of the ingot cross section. In order to eliminate or substantially reduce the thickness of this outer dendritic layer the thermal conductivity of the upper region of the mold 36 is reduced by means of a partial mold liner 62 formed from an insulator such as a ceramic. The ceramic mold liner 62 extends from the ceramic liner 55 of the mold cover 54 down into the mold 36 cavity for a distance sufficient so that the magnetic stirring force field of the two pole motor stator 51 is intercepted at least in part by the partial ceramic mold liner 62. The ceramic mold liner 62 is a shell which conforms to the internal shape of the mold 36 and is held to the mold wall 38. The mold 36 comprises a duplex structure including a low heat conductivity portion defined by the ceramic liner 62 and a relatively higher heat conductivity portion defined by the exposed portion of the mold wall 38.

The liner 62 postpones solidification until the molten metal is in the region of the strong magnetic stirring force. The low heat extraction rate associated with the liner 62 generally prevents solidification in that portion of the mold. Generally solidification does not occur except towards the downstream end of the liner 62 or just thereafter. The shearing process resulting from the applied rotating magnetic field will further override the tendancy to form a solid shell in the region of the liner 62. This region 62 or zone of low thermal conductivity thereby helps the resultant rheocast casting 32′ to have a degenerate dendritic structure throughout its cross section even up to its outer surface.

Below the region of controlled thermal conductivity defined by the liner 62, the normal type of water cooled metal casting mold wall 38 is present. The high heat transfer rates associated with this portion of the mold 36 promote ingot shell formation. However, because of the zone 62 of low heat extraction rate even the peripheral shell of the casting 32′ should consist of degenerate dendrites in a surrounding matrix.

It is preferred in order to form the desired rheocast structure at the surface of the casting to effectively shear any initial solidified growth from the mold liner 62. This can be accomplished by ensuring that the field associated with the motor stator 51 extends over at least that portion of the liner 62 at which solidification is first initiated.

The dendrites which initially form normal to the periphery of the casting mold 36 are readily sheared off due to the metal flow resulting from the rotating magnetic field of the induction motor stator 51. The dendrites which are sheared off continue to be stirred to form degenerate dendrites until they are trapped by the solidifying interface 63. Degenerate dendrites can also form directly within the slurry because the rotating stirring action of the melt does not permit preferential growth of dendrites. To insure this the stator 51 length should preferably extend over the full length of the solidification zone. In particular the stirring force field associated with the stator 51 should preferably extend over the full length and cross section of the solidification zone with a sufficient magnitude to generate the desired shear rates.

It is preferred that the entire casting solidify the stator 51 field in order to produce castings with proper rheocast structure through their entire cross section. Therefore, the casting apparatus 10 to 10′ should preferably be designed to ensure that the entire solidification zone or sump region is within the stator 51 field. This may require extra long stators 51 to be provided to handle some types of casting.

The method and apparatus described herein can be extended to non-circular cross section molds 36 by constructing non-circular induction motor stators to provide stirring similar to that described by reference to Fig. 3.

We have found that two competing processes shearing and solidification can be used to control casting. The shearing produced by the electromagnetic field can be made equivalent to or greater than that obtainable by mechanical stirring. The interaction between shear rates and cooling rates causes higher stator currents to be required for continuous type casting then are required for static casting.

It has been found that the effects of the experimental variables in the process can be predicted from a consideration of two dimensionless groups, namely β and N as follows:–

$$B = \sqrt{j\omega\sigma\mu_o R^2} \qquad (1)$$

$$N = \frac{\sigma R^2 B_{\omega}^2}{\eta_o} \qquad (2)$$

where

$j = \sqrt{-1}$
ω = angular line frequency
σ = melt electrical conductivity
μ_o = magnetic permeability
R = melt radius
$B_{\theta w}$ = magnetic induction at the mold wall
η_o = melt viscosity.

The first group, β, is a measure of the field geometry effects, while the second group, N, appears as a coupling coefficient between the magnetomotor body forces and the associated velocity field. The computed velocity and shearing fields for a single value of β as a function of the parameter N can be determined.

From these determinations it has been found that the shear rate increases sharply toward the outside of the mold where it reaches its maximum. This maximum shear rate increases with increasing N. It has been concluded that the shearing is produced in the melt because the peripheral boundary or mold wall is rigid. Therefore, even when a solidifying shell is present, there should still be shear stresses in the melt and they should be maximal at the liquid solid interface 35 or 63. Further because there are always shear stresses at the advancing interface 35 or 63 it is possible to make a full section ingot 32 or 32′ with the appropriate degenerate dendritic rheocast structure.

The following Examples illustrate the invention:–

EXAMPLE I

Using an apparatus 10 similar to that shown in Figs. 1 and 2 a semi-solid thixotropic alloy slurry was made from each of two separate aluminum alloys, 6061 and A 356. The mold comprised a stainless steel crucible. The mold was charged with molten metal corresponding to the respective alloy. The molten metal was cooled at an average cooling rate of 50°C per minute while under the influence of a rotating magnetic field generated, when a current of 15 amps at 60 hertz was passed through the two pole three-phase induction motor stator 27. The magnetic induction at the crucible wall 13 was 300 gauss. The resulting alloys had a typical rheocast structure comprising generally spheroidal primary solids surrounded by a solid matrix of different composition.

EXAMPLE II

Ingots 2.5 inches in diameter of alloy 6061 were cast using an apparatus 10′ similar to that shown in Figs. 6 and 7. The bottom block 37 was lowered and the casting was drawn from the mold 36 at speeds of from about 8 to 14 inches per minute. The two pole three-phase induction motor stator 51 current was varied between 5 and 35 amps. It was found that at the low current end of this range, a fine dendritic grain structure was produced but not the characteristic structure of a rheocast thixotropic slurry. At the high current end of the range particularly in and around 15 amps fully non-dendritic structures were generated having a typical rheocast structure comprising generally spheroidal primary solids surrounded by a solid matrix of different composition.

The mold covers 14 and 54 by enclosing the mold cavity except for the small centrally located opening 17 or 56 serve not only to prevent spillage of molten metal but also to prevent the formation of a U-shaped cavity in the end of the rheocasting. By adding sufficient molten metal to the mold to at least partially fill the funnel 16 or 57 it is possible to insure that the mold cavity is completely filled with molten metal and slurry. The cover 14 or 54 offsets the centrifugal forces and prevents the formation of the U-shaped cavity on solidification. By completely filling the mold oxide entrainment in the resulting casting is substantially reduced.

While it is preferred that the stirring force due to the magnetic field extend over the entire solidification zone it is recognised that the shearing action on the dendrites results from the rotating movement of the melt. This metal stirring movement can cause shearing of dendrites outside the field if the moving molten metal pool extends outside the field.

Dendrites will initially attempt to grow from the sides or wall of the mold. The solidifying metal at the bottom of the mold may not be dendritic because of the comparatively low heat extraction rate which promotes the formation of more equiaxed grains.

Suitable state currents for carrying out the process will vary depending on the stator which is used. The currents must be sufficiently high to provide the desired magnetic field for generating the desired shear rates.

Suitable sheat rates for carrying out the process of this invention comprise from at least about 100 sec. $^{-1}$ to about 1500 sec. $^{-1}$ and preferably from at least about 500 sec. $^{-1}$ to about 1200 sec. $^{-1}$. For aluminum and its alloys a shear rate of from about 700. $^{-1}$ to about 1100 sec. $^{-1}$ has been found desirable.

The average cooling rates through the solidification temperature range of the molten metal in the mold should be from about 0.1°C per minute to about 1000°C per minute and preferably from about 10°C per minute to about 500°C per minute. For aluminum and its alloys an average cooling rate of from about 40°C per minute to about 500°C per minute has been found to be suitable. The efficiency of the magnetohydrodynamic stirring allows the use of higher cooling rates than with prior art stirring processes. Higher cooling rates yield highly desirable finer grain structures in the resulting rheocasting. Fur-

ther, for continuous rheocasting higher throughput follows from the use of higher cooling rates.

The parameter $|\beta^2|$ (β defined by equation (1)) should comprise from about 1 to about 10 and preferably from about 3 to about 7. The parameter in N (defined by equation (2)) should comprise from about 1 to about 1000 and preferably from about 5 to about 200.

The angular line frequency ω for a casting having a radius of from about 1" to about 10" should be from about 3 to about 3000 hertz and preferably from about 9 to about 2000 hertz.

The magnetic field strength which is a function of the angular line frequency and the melt radius should comprise from about 50 to 1500 gauss and preferably from about 100 to about 600 gauss.

The particular parameters employed can vary from metal system to metal system in order to achieve the desired shear rates for providing the thixotropic slurry. The appropriate parameters for alloy systems other than aluminum can be determined by routine experimentation in accordance with the principles of this invention.

Soldification zone as the term is used in this application refers to the zone of molten metal or slurry in the mold wherein solidification is taking place. Magnetohydrodynamic as the term is used herein refers to the process of stirring molten metal or slurry using a moving or rotating magnetic field. The magnetic stirring force may be more appropriately referred to as a magnetomotive stirring force which is provided by the moving or rotating magnetic field of this invention.

The techniques described herein are applicable to the casting of a range of materials as set forth in the prior art including but not limited to aluminum and its alloys, copper and its alloys and steel and its alloys.

CLAIMS

1. An apparatus for forming a semi-solid thixotropic alloy slurry, consisting of degenerate dendrite primary solid particles in a surrounding matrix of molten metal, said apparatus comprising:

means for containing molten metal;

means for controllably cooling said molten metal in said containing means; and

means for mixing said molten metal for shearing dendrites formed in a solidification zone as said molten metal is cooled for forming said slurry;

wherein said mixing means comprises means for generating a moving, non-zero magnetic field across said cross section of said containing means and over said entire solidification zone, said moving magnetic field providing a magnetomotive stirring force of sufficient magnitude to provide said mixing of said molten metal.

2. An apparatus as claimed in claim 1, wherein said generating means provides a magnetic field which moves transversely of a longitudinal axis of said containing means.

3. An apparatus as claimed in claim 1 wherein said generating means provides a rotating magnetic field.

4. An apparatus as claimed in claim 3 wherein said magnetomotive stirring force is directed tangentially of said containing means for causing said molten metal and slurry to rotate in said containing means, whereby said rotation of said molten metal and slurry is effective to provide said shearing of said dendrites.

5. An apparatus as claimed in any one of claims 1 to 4, wherein said magnetomotive stirring force is directed normal to a growth direction of said dendrites.

6. An apparatus as claimed in any one of claims 1 to 5, wherein said rotating magnetic field generating means comprises a multiphase, two pole induction motor stator.

7. An apparatus as claimed in claim 6, wherein said motor stator comprises a three-phase motor stator.

8. An apparatus as claimed in claim 6 or 7, wherein said containing means comprises a mold for forming a rheocasting from said slurry, said stator being arranged surrounding said mold, said mold defining a desired longitudinal casting axis.

9. An apparatus as claimed in claim 8, wherein said mold has a circular cross section and said stator is arranged concentrically about said mold and said casting axis.

10. An apparatus as claimed in claim 8, wherein said mold has a rectangular cross section and said stator comprises a rectangular induction motor stator.

11. An apparatus as claimed in claim 8, 9 or 10, wherein said mold is formed of metal and includes a mold wall and wherein said cooling means comprises a manifold arranged surrounding said mold for directing water against said mold wall.

12. An apparatus as claimed in claim 11, wherein said mold comprises a static casting mold.

13. An apparatus as claimed in claim 11, wherein said mold comprises a continuous or semi-continuous casting mold.

14. An apparatus as claimed in any one of claims 8 to 13, wherein said cooling means provides an average cooling rate through a solidification temperature range of said molten metal of 0.1°C/min. to 1000°C/min.

15. An apparatus as claimed in any one of claims 8 to 14, wherein said magnetomotive force provides shear rates of 100 sec.$^{-1}$ to 1500 sec.$^{-1}$.

16. An apparatus as claimed in any one of claims 8 to 15, and further including means for preventing said molten metal or slurry from spilling out of said mold and for prevent-

ing the formation of a solidification cavity in the resulting rheocasting.

17. An apparatus as claimed in claim 16 wherein said spilling and cavity preventing means comprises a mold cover member which substantially encloses said mold except for a central opening therein through which molten metal is introduced into said mold.

18. A casting apparatus, substantially as described herein with reference to Figs. 1 and 2, or to Fig. 3 or to Figs. 6 and 7 of the accompanying drawings.

19. A process for forming a semi-solid thixotropic alloy slurry, said slurry comprising degenerate dendrite primary solid particles in a surrounding matrix of molten metal, said process comprising;

providing a means for containing molten metal having a desired cross section;

controllably cooling said molten metal in said containing means; and

generating a moving, non-zero magnetic field across said cross section of said containing means and over said entire solidification zone, said moving magnetic field providing a magnetomotive stirring force of sufficient magnitude to provide mixing of said molten metal.

20. A process as claimed in claim 19, wherein said generating step comprises providing a magnetic field which moves transversely of a longitudinal axis of said containing means.

21. A process as claimed in claim 19, wherein said generating step comprises providing a rotating magnetic field.

22. A process as claimed in claim 19, 20 or 21, wherein said magnetomotive stirring force is directed tangentially of said containing means for causing said molten metal and slurry to rotate in said containing means, whereby said rotation of said molten metal and slurry is effective to provide said shearing of said dendrites.

23. A process as claimed in claim 22, wherein said magnetomotive stirring force is directed normal to a growth direction of said dendrites.

24. A process as claimed in claim 22, wherein said magnetic field is generated by a multiphase, two pole, induction motor stator.

25. A process as claimed in any one of claims 19 to 24, wherein said containing means comprises a mold and further including the step of forming a rheocasting from said slurry.

26. A process as claimed in claim 25, wherein said rheocasting has a circular cross section.

27. A process as claimed in claim 25, wherein said rheocasting has a rectangular cross section.

28. A process as claimed in claim 25, 26 or 27, wherein said rheocasting is carried out statically.

29. A process as claimed in claim 25, 26 or 27, wherein said step forming said rheocasting is carried out continuously or semi-continuously.

30. A process as claimed in any one of claims 19 to 29, wherein said cooling means provides an average cooling rate through a solidification temperature range of said molten metal of 0.1°C/min. to 1000°C/min.

31. A process as claimed in any one of claims 19 to 30., wherein said magnetomotive force provides shear rates of 100 sec. $^{-1}$ to 1500 sec. $^{-1}$.

32. A casting process substantially as described herein with reference to Figs. 1 to 3 and to Figs. 5 to 7 of the accompanying drawings.

33. A casting formed by a process as claimed in any one of claims 19 to 32.

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